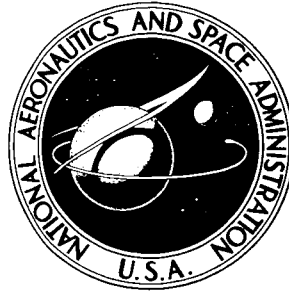


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EFFECTIVENESS OF FLEXIBLE AND RIGID RING BAFFLES FOR DAMPING LIQUID OSCILLATIONS IN LARGE-SCALE CYLINDRICAL TANKS

by David G. Stephens and Harland F. Scholl

Langley Research Center

Langley Station, Hampton, Va.

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SUMMARY

An investigation was conducted to determine the effectiveness of lightweight, flexible baffles for damping liquid oscillations in relatively large cylindrical tanks. The free decay of the fundamental antisymmetric liquid mode was measured in 30- and 112-inch (76.2- and 284-cm) diameter rigid tanks fitted with both flexible and rigid annular ring baffles. Data are presented to illustrate the variation of liquid damping with slosh amplitude, baffle location, tank size, and baffle flexibility. Comparative flexible and rigid baffle damping results are presented in terms of nondimensional parameters which cover a wide range of liquid velocity and baffle flexibility conditions. In addition, measured slosh frequencies and rigid baffle damping coefficients are compared with available theory. Results indicate that slosh damping comparable to that provided by a rigid baffle can be obtained through the use of smaller, much less massive, flexible baffles.

INTRODUCTION

Antislosh baffles are usually required in liquid propellant launch vehicles in order to minimize propellant oscillations. A typical baffle configuration consists of a number of rigid annular rings fitted around the internal periphery of the tank. The size and number of baffles required for adequate damping can be determined from semiempirical relationships such as the one presented by Miles in reference 1. Although such baffles are effective in attenuating slosh, they usually comprise a high percentage of the tank weight. Therefore, an improvement in baffle efficiency, that is, damping per unit of baffle weight, is highly desirable and could result in a substantial reduction in system weight.

Limited small-scale model studies have indicated that improved damping can be obtained by the use of lightweight flexible baffles. This concept was discussed in reference 2 and was later experimentally verified in reference 3 where a flexible ring baffle was shown to be superior to a rigid ring for damping liquid oscillations in a spherical

tank. More detailed investigations are reported in references 4 and 5. In reference 4, rectangular plates having various degrees of flexibility were attached to a pendulum apparatus and allowed to oscillate in a tank of quiescent water. Within the velocity range of practical interest, the damping coefficients associated with the plates or baffles of optimum flexibility were found to be considerably higher than those associated with a rigid baffle. These findings were substantiated in reference 5, which demonstrated the effectiveness of flexible baffles for damping slosh modes in a small rectangular tank.

The results of these model studies indicate the excellent potential of flexible baffles for providing high damping per unit of weight. The objective of this investigation is to extend these programs to include tanks of a size more representative of actual space vehicles. The effectiveness of ring baffles for damping the slosh modes in cylindrical tanks of 30- and 112-inch (76.2- and 284-cm) diameters is examined. The nature and magnitude of damping factors associated with baffles ranging from rigid to extremely flexible are presented for a wide range of liquid displacement or velocity conditions. In addition, measured slosh frequencies and rigid baffle damping results are presented and compared with the available theory.

SYMBOLS

D	width of baffle, inches (cm)
d	distance of baffle below free surface, inches (cm)
E	modulus of elasticity of baffle material, pounds/inch ² (Newtons/cm ²)
F	flexibility parameter defined by equation (7)
f	frequency of slosh mode, cycles/second (hertz)
N _{Fr}	Froude number
g	acceleration due to gravity, inches/second ² (cm/second ²)
H	tank length, inches (cm)
h	liquid depth, inches (cm)
l	distance of baffle above tank bottom, inches (cm)

N	number of cycles
P	period parameter defined by equation (1)
p	dynamic pressure, pounds/inch ² (Newtons/cm ²)
R	cylinder radius, inches (cm)
T	period of liquid oscillation, seconds
t	thickness of baffle, inches (cm)
U	velocity of liquid at baffle location, inches/second (cm/second)
V	baffle velocity, inches/second (cm/second)
X	liquid amplitude at baffle location, inches (cm)
z	distance from free surface (positive downward into liquid), inches (cm)
Δ	baffle deflection, inches (cm)
δ	logarithmic decrement, $\frac{1}{N} \log_e \frac{\zeta_n}{\zeta_{N+n}}$
ξ	displacement amplitude of liquid surface, inches (cm)
η	baffle efficiency, damping/unit baffle weight
ν	Poisson's ratio for baffle material
ρ	liquid mass density, pound-seconds ² /inch ⁴ (kilograms/cm ³)
ω	circular frequency, radians/second

Subscripts:

l	partial baffle width
b	baffle

e	experiment
flex	flexible
n	nth cycle of vibration
r	rigid baffle
t	theory

APPARATUS AND TEST PROCEDURE

Tanks

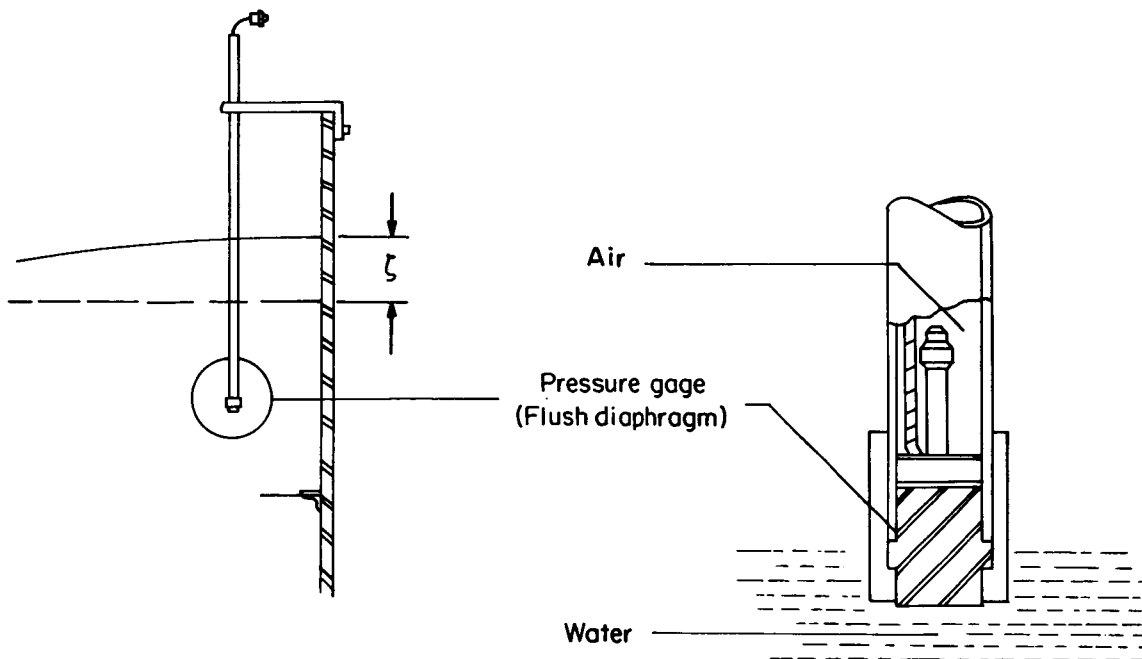
Two vertically oriented right circular cylindrical tanks having diameters of 30 and 112 inches (76.2 and 284 cm) were utilized in this investigation. Most of the data were obtained in the larger tank which consisted of a 0.625-inch (1.58-cm) thick steel-walled cylinder with an ellipsoidal bottom, as shown in figure 1. The smaller tank had a 0.016-inch (0.0406-cm) aluminum cylindrical section and a 0.5-inch (1.27-cm) aluminum base-support plate. Two relatively long narrow plates were vertically mounted along the tank walls at the desired antinode locations of the fundamental mode to prevent any rotational drift of the slosh plane. The pertinent dimensions of both tanks are shown in figure 2. These tanks were considered to be rigid and remained stationary during testing.

Baffles

The baffles consisted of continuous annular rings having the dimensions and physical properties given in table I. The baffle under study was clamped to an angle bracket which was fixed to the tank wall. The position of the baffle with respect to the quiescent surface d (fig. 2) was varied by changing the level of the water which was used as the test liquid.

Instrumentation

The displacement amplitudes of the liquid in the 112-inch (284-cm) and 30-inch (76.2-cm) diameter tanks were sensed by a pressure transducer and a capacitance-wire system, respectively. The pressure system consisted of a strain-gage differential pressure transducer (flat response from 0 to 700 cps (hertz)) which was sealed in a 0.75-inch (1.91-cm) diameter tube open to the atmosphere as shown in sketch (a).



Sketch (a).- Pressure-sensitive liquid amplitude transducer.

The sensing element was placed a fixed distance below the quiescent surface at the location of the liquid antinode. The amplitude of the output signal was directly proportional to the liquid amplitude, the constant of proportionality being determined in a separate calibration in which the liquid amplitude was read directly from a scale along the tank wall. The capacitance-wire transducer system utilized in the 30-inch (76.2-cm) tank is described fully in reference 6. Two capacitance probes were mounted at the antinode points and yielded electrical outputs proportional to the surface amplitude. The transducer signals were recorded (flat response from 0 to 90 cps (hertz)) as oscillograms and the damping of the oscillation was determined from these records.

Procedure

The test procedure was essentially the same for both systems. The tank was filled to a selected level d/R above the baffle, which for these tests ranged from 0.2 to 0.4. The liquid was then excited in the fundamental antisymmetric mode by manually applying a vertical excitation at the antinode with a plunger. (See fig. 1(b).) Upon reaching the highest attainable amplitude ζ , the plunger was removed and the free decay of the liquid amplitude was recorded. This procedure was repeated several times at each baffle location d/R and the results were averaged to determine the damping.

NONDIMENSIONAL PARAMETERS

The liquid slosh characteristics, baffle flexibility, and liquid damping may be specified by three nondimensional parameters: the period parameter which describes the liquid velocity conditions in the vicinity of the baffle; a flexibility parameter which defines the deflection characteristics of the baffle per unit loading; and the relative damping parameter which is a comparison of flexible and rigid baffle damping coefficients. The period parameter P is defined in reference 7 as

$$P = UT/D \quad (1)$$

where U is the maximum fluid velocity at the baffle location, T is the natural period of the oscillation, and D is the baffle width. This parameter was shown in reference 7 to be similar to the Strouhal number and important in correlating drag coefficients of plates in an oscillating flow. The maximum vertical velocity in a cylindrical tank due to the antisymmetric mode, as obtained from a potential solution (no baffle), may be written as (see ref. 1)

$$U = \omega \zeta \frac{\sinh \left[1.84 \left(\frac{h-z}{R} \right) \right]}{\sinh \left(1.84 \frac{h}{R} \right)} \quad (2)$$

where ω is the natural slosh frequency, ζ is maximum displacement amplitude at the surface, z is a distance below the quiescent surface, R is the tank radius, and h is the liquid depth. When equation (2) is substituted for U in equation (1), the period parameter becomes

$$P = \frac{2\pi\zeta}{D} \frac{\sinh \left[1.84 \left(\frac{h-z}{R} \right) \right]}{\sinh \left(1.84 \frac{h}{R} \right)} \quad (3)$$

which may be physically interpreted as the maximum distance traveled by a liquid particle at the antinode divided by the baffle width. Damping or loss coefficients associated with flexible baffles, as determined by the pendulum apparatus of reference 4, were correlated for period parameters ranging from 2 to 40. The damping associated with the lightweight flexible baffles exceeded that of a rigid baffle for period parameters of 10 or less. For most launch vehicle applications, the region of practical importance appears to be less than 10. In fact, a period parameter of 2 appears to be the upper limit for certain launch vehicle designs such as the first stage of the Saturn V. For this study, the period parameter ranged from 0.6 to 2, the latter value being the highest attainable and having the appearance of relatively severe slosh.

The flexibility parameter was first used in reference 4 to describe the deflection or flexibility characteristics of cantilever baffles. The parameter may be interpreted as the baffle deflection for a period parameter of unity divided by the baffle width. The bending deflection Δ of a cantilever plate of length D_1 may be written as

$$\Delta \propto D_1^4 \left(\frac{1 - \nu^2}{Et^3} \right) p \quad (4)$$

where t is the plate or baffle thickness, E is the modulus of elasticity of the baffle material, ν is Poisson's ratio, and p is the pressure loading. The pressure p may be considered as being

$$p \propto \rho U^2 \quad (5)$$

where ρ is the mass density of the liquid. For a period parameter of unity, the pressure may also be written as

$$p \propto \rho \frac{D_1^2}{T^2} \quad (6)$$

Thus when equation (6) is substituted for p into equation (4), the flexibility parameter for the case under study is

$$F = \frac{\Delta}{D_1} = D_1^3 \left(\frac{1 - \nu^2}{Et^3} \right) \frac{\rho D_1^2}{T^2} f \left(\frac{D_1}{R} \right) \quad (7)$$

where D_1 is the width of the flexible portion of the baffle (see table I) and $f \left(\frac{D_1}{R} \right)$ is a radius correction factor (see ref. 4) which for most applications is close to one. It should be noted that the actual flexibility of a thin flexible baffle in a cylindrical tank may be somewhat less than indicated by equation (7) since tension or membrane stiffness would tend to limit the displacement.

It is interesting to note the similarity between the flexibility parameter and the Froude number. In the case of a rectangular cantilever baffle, for example, the natural frequency may be written as (see ref. 8)

$$\omega_b^2 \propto \frac{t^3}{D_1^4} \frac{E}{(1 - \nu^2)} \frac{g}{p} \quad (8)$$

where g is the acceleration due to gravity. If equation (6) is substituted for pressure p , equation (8) may be written as

$$\omega^2 \propto \frac{t^3}{D_1^4} \frac{E}{(1 - \nu^2)} \frac{gT^2}{\rho D^2} \quad (9)$$

Therefore, the flexibility parameter is

$$F \propto \frac{g}{\omega^2 D_1} = \frac{g D_1}{\omega^2 D_1^2} = \frac{g D_1}{V^2} = \frac{1}{N_{Fr}} \quad (10)$$

which is the inverse of the Froude number. The flexibility parameter and/or Froude number include the acceleration due to gravity and therefore these parameters may be utilized in model testing to obtain representative values of damping in large scale tanks accelerating under varying g conditions.

Another parameter of interest is the relative damping δ/δ_r which is the ratio of the damping decrement provided by the flexible baffle to the damping provided by a rigid baffle of the same width and under similar flow conditions. The decrement is defined as

$$\delta = \frac{1}{N} \log_e \frac{\xi_n}{\xi_{N+n}} \quad (11)$$

where N is the number of cycles occurring over the amplitude range (ξ_n, ξ_{N+n}) .

DATA REDUCTION

The maximum surface amplitude for each cycle of slosh and the slosh frequency was determined from the oscillogram. The corresponding period parameters were then calculated by using equation (3) and were plotted for each cycle as shown by the sample data in figure 3. The slopes of the resulting curves, which are proportional to the damping decrements, were determined at period parameters of 2, 1.5, 1, 0.8, and 0.6 for each baffle and baffle location with an average scatter of ± 10 percent. For purposes of comparison, the slopes associated with the flexible baffles were divided by those of the rigid baffles at the same value of depth and period parameter. The "smooth wall" damping was not subtracted from the total measured decrement since it is essentially negligible (see ref. 6) for baffled tanks of the size considered in this investigation.

In addition, the rigid-baffle damping decrements and the measured slosh frequencies were compared with the available theory. The damping provided by a rigid baffle, as derived by Miles in reference 1, is given by the semiempirical relationship

$$\delta_r = (2\pi) 2.83e^{-4.60d/R} a^{3/2} (\zeta/R)^{1/2} \quad (12)$$

where a is the fractional part of the cross-sectional area of the tank blocked by the baffle

$$a = \frac{R^2 - (R - D)^2}{R^2} \quad (13)$$

The natural frequency of the fundamental antisymmetric slosh mode in an unbaffled cylindrical tank is given by (see ref. 4, for example)

$$f = \frac{1}{2\pi} \sqrt{\frac{1.84g}{R} \tanh\left(1.84 \frac{h}{R}\right)} \quad (14)$$

RESULTS AND DISCUSSION

The test program consisted of an isolation and examination of the liquid damping for the variables: liquid amplitude ζ/R ; baffle location d/R ; tank size R ; and baffle flexibility F . The dependency of the damping on each of these variables is illustrated with representative data. The damping will then be presented in terms of nondimensional parameters to illustrate the relative effectiveness of flexible baffles over the range of liquid velocity and baffle flexibility conditions believed to be of interest for launch vehicle applications. As an adjunct to these studies, rigid baffle damping characteristics are presented in detail and compared with the semiempirical relationship of Miles (ref. 1). Finally, the slosh frequency is presented for each baffle and baffle location and compared with the theoretical value for an unbaffled tank. Baffle support systems, cryogenic temperature effects, and stress analyses are not considered in this paper.

Liquid Damping Characteristics

Effect of amplitude. - The dependency of the liquid damping on surface amplitude ζ/R is illustrated in figure 4. The damping in terms of a logarithmic decrement is presented for the rigid baffle and two representative flexible baffles installed at three locations in the 112-inch tank. The dependency of damping on amplitude is more pronounced for the rigid baffle than for the flexible baffles. In fact, in many applications a linear or viscous representation may be sufficient to specify the flexible baffle damping, and thus simplify the analytical or design problems. The relatively high damping associated with the flexible baffles in the region of low liquid amplitude is highly desirable since it would retard the initiation or build up of slosh. When the magnitudes of damping for each baffle at corresponding amplitudes and depths are compared, the flexible baffle damping is seen to be considerably higher. In fact, over the range of amplitude and depth covered in all tests, the damping exhibited by the flexible baffles exceeded the corresponding rigid

baffle damping without exception. The reason for this higher damping is believed to be related to an increase in relative velocity associated with a flexible baffle. It was observed in these tests that the baffle displacement led the liquid surface displacement by 90° or more and resulted in higher relative velocities and increased vorticity. This phenomenon is discussed in more detail in reference 4 where the results of an extensive flow-visualization program are described.

Effect of baffle depth.- The effect of baffle location on the magnitude of the damping is illustrated in figure 5 for the three baffles shown in the previous section. The liquid damping decreases as the distance of the baffle below the surface increases because of the approximately exponential reduction in liquid velocity with depth. The flexible baffles do not, however, display as great a percentage reduction in damping with depth as does a rigid baffle. This characteristic may be beneficial since it tends to smooth out the damping "peaks and valley" which occur in a draining tank fitted with a series of baffles.

Effect of period parameter.- The damping is presented as a function of the nondimensional period parameter UT/D in figure 6. The period parameter is a function of both depth and surface amplitude (see eq. (3)) since U is defined as the theoretical liquid velocity at the baffle location. In fact, the parameter may be alternately written

as $2\pi X/D$ (where $X = \frac{\xi \sinh 1.84 \left(\frac{h-z}{R} \right)}{\sinh 1.84 \frac{h}{R}}$) which is the ratio of the liquid displacement

at the baffle location to the baffle width. Thus, figure 4 and figure 6 differ essentially in the definition of amplitude, the former specifying the amplitude at the surface and the latter specifying amplitude at the baffle. As shown, the magnitude of the damping for a given baffle and period parameter depends upon, and decreases with, an increase in depth d/R (see ref. 1). The dependency on depth noted in figure 6 can be easily explained. For a given value of the period parameter, the energy loss per cycle as defined by Miles in reference 4 is the same for each of the baffle locations d/R . However, the total energy is higher at larger values of d/R since higher surface amplitudes are required to maintain a given period parameter. Therefore, the ratio of energy loss per cycle to total energy which is proportional to the logarithmic decrement decreases with increasing depth for given values of period parameter and explains the depth dependency noted in figure 6. However, it will be shown in a later section that the relative damping effectiveness, that is the ratio of the damping provided by a flexible baffle to that of a rigid baffle, may be considered to be independent of depth.

Effect of diameter.- Damping factors obtained for the rigid baffle in the 30-inch-diameter tank at depths d/R of 0.2 and 0.3 are presented in figure 7 and compared with values obtained in the 112-inch (284-cm) tank (fig. 4(a)) to illustrate size effects. Within the experimental accuracy of these tests, the results indicate that geometrically scaled systems have the same damping at corresponding values of the period parameter.

Relative Baffle Effectiveness

Period parameter relationship.- The relative damping is presented in figure 8 as a function of the period parameter. The relative damping is the ratio, at corresponding depths and period parameters, of the rigid and flexible baffle damping factors. The data were obtained over a depth range d/R of 0.2 to 0.4 as shown by the symbols. Over this range, the data may be correlated by a single curve which suggests that the relative damping is independent of depth. For low values of the period parameter, the relative damping is comparatively high. As the parameter increases, the relative damping, in general, tends to decrease; however, the values are greater than one throughout the range examined. The greater effectiveness of the flexible baffles in the region of low period parameters is due to the relatively high damping provided by the flexible baffles in the region of low liquid amplitudes as previously discussed. Again, this condition appears to be a desirable situation for preventing the initiation and subsequent buildup of slosh.

Flexibility relationship.- The results of all the tests are summarized in figure 9 where the relative damping is presented as a function of the flexibility parameter. These data were obtained from figures 8(a) to 8(g) at period parameters ranging from 0.6 to 2. Throughout this range of baffle flexibility and period parameter, the relative damping exceeds unity; this fact illustrates the superiority of the flexible baffle as an antislosh device. As the baffle becomes more flexible ($F > 10^{-6}$), the relative damping increases and reaches a maximum at a flexibility value which is dependent upon the value of the period parameter as discussed in reference 4. For a period parameter of 2, for example, the highest damping occurs at a flexibility of about 10^{-2} which is in agreement with references 4 and 5. It should be noted that as a baffle becomes more flexible ($F > 10^{-6}$) not only does the relative damping increase but also the baffle weight decreases and, as a result, there is a very substantial improvement in baffle efficiency. The data shown by the solid symbols were obtained in the 30-inch (76.2-cm) tank. The relatively good agreement illustrates the significance of the nondimensional parameters for correlating and extrapolating data. These results along with those of reference 4 are believed to be sufficient for the design of flexible baffles to meet damping requirements in a large variety of launch vehicles.

Baffle efficiency.- Although the flexible baffle provides considerably higher damping coefficients than a comparable rigid baffle, the greatest advantage of the flexible baffle is undoubtedly in size and weight reduction. For example, in figure 9 the flexible baffle exhibited damping coefficients approaching 2.5 times that of the rigid case; however, for the same flexibility, the baffle weight is approximately 40 times less than that of the rigid baffle. To illustrate, the results shown in figure 9 are replotted in figure 10 with the baffle weight included. For a given material, the baffle efficiency η is defined as

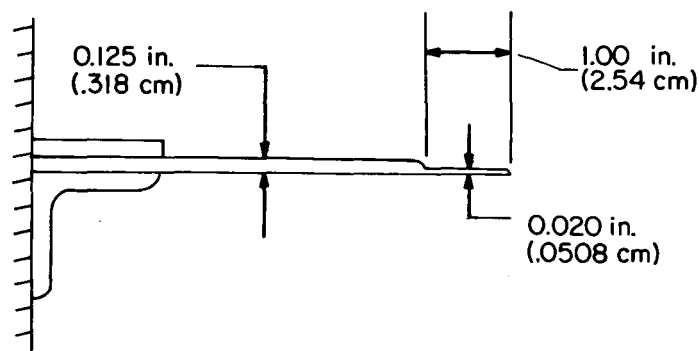
$$\eta = \frac{(\delta/t)_{\text{flex}}}{(\delta/t)_r}$$

which is presented as a function of flexibility for a range of period parameters. Values of η approaching 100 are obtained in the flexibility region of 2×10^{-1} . These values may vary somewhat depending upon the value of thickness t selected for the rigid baffle (0.125 in. (0.32 cm)). The results do, however, clearly demonstrate that damping comparable to that provided by a rigid baffle can be obtained by the use of smaller, less massive, flexible baffles.

Rigid Baffle Damping

Comparison with theory.- Rigid baffle damping was studied in detail since it was used as the standard in determining the effectiveness of the flexible baffles. Despite the general use of rigid baffles, there is virtually no published information on the characteristics of such baffles in large tanks and no verification of Miles' damping theory in tanks of large size. Because of the common usage of Miles' theory (ref. 1), particular effort was made to compare the experimental results with predicted values. Data obtained from three or more tests are presented in figure 11 and compared with theory. In general, the theoretical curve is about 20 percent higher than the average experimental values. When the assumptions and approximations made in the derivation are considered, this agreement is believed to be good and should be sufficiently accurate for most applications. The greatest scatter in the experimental data is found in the region of high surface amplitude and low baffle depth which is attributed to the turbulent nature of the liquid in this region.

Thickness effects.- To determine the effect of baffle thickness and/or edge condition on the magnitude of the damping, the 0.125-inch (0.318 cm) rigid baffle was machined to a sharp edge as shown in sketch (b). Data obtained at depths of 0.2, 0.3, and 0.4 are presented in figure 12 (flagged symbols) along with the rigid baffle averages. It is concluded



Sketch (b).- Sharp edge baffle.

that the edge conditions of a baffle which has a thickness-width ratio of the order utilized in these tests ($t/D < 0.022$) will have little, if any, effect on the magnitude of the damping. (See ref. 9.)

Slosh Frequency

The frequency of the slosh mode was determined for each of the baffle conditions. The results are presented in table II for all the baffles and in figure 13 for the rigid, medium, and high flexibility baffles. In all cases, the presence of a baffle lowered the slosh frequency in a manner similar to that described in reference 2 over the depth range of d/R of 0.2 to 0.4. The maximum deviation in frequency from the value calculated for a smooth wall tank was 2.8 percent and was observed for the more rigid baffles. The flexible baffles have considerably less effect on the frequency.

CONCLUSIONS

An investigation was conducted to determine the effectiveness of lightweight flexible ring baffles for damping liquid oscillations in relatively large cylindrical tanks. Results substantiate the findings of model studies and demonstrate that damping comparable to that provided by a rigid baffle can be obtained through the use of smaller, less massive, flexible baffles. The following specific comments are offered based on the range of variables covered by these tests:

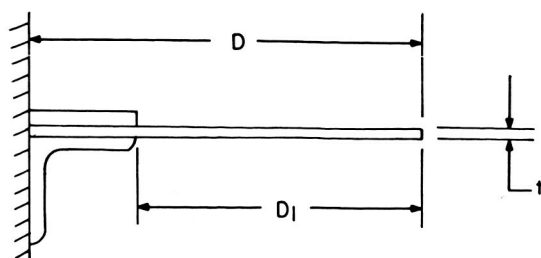
1. A flexible baffle provides damping of a magnitude comparable to or greater than that of a rigid baffle under similar oscillatory flow.
2. The efficiency or damping per unit of weight associated with a flexible baffle may greatly exceed that of a rigid baffle.
3. The magnitude of the damping provided by a flexible baffle is dependent upon and may be scaled by two nondimensional parameters: a period parameter, proportional to the ratio of liquid amplitude to baffle width and a flexibility parameter, proportional to the ratio of baffle deflection to baffle width.
4. The damping values associated with a rigid baffle are about 20 percent lower than those predicted by Miles' equation which should be sufficiently accurate for most applications.
5. A decrease in slosh frequency due to the presence of a flexible baffle is less than the shift inherent with a rigid baffle.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 6, 1966,
124-11-05-26-23.

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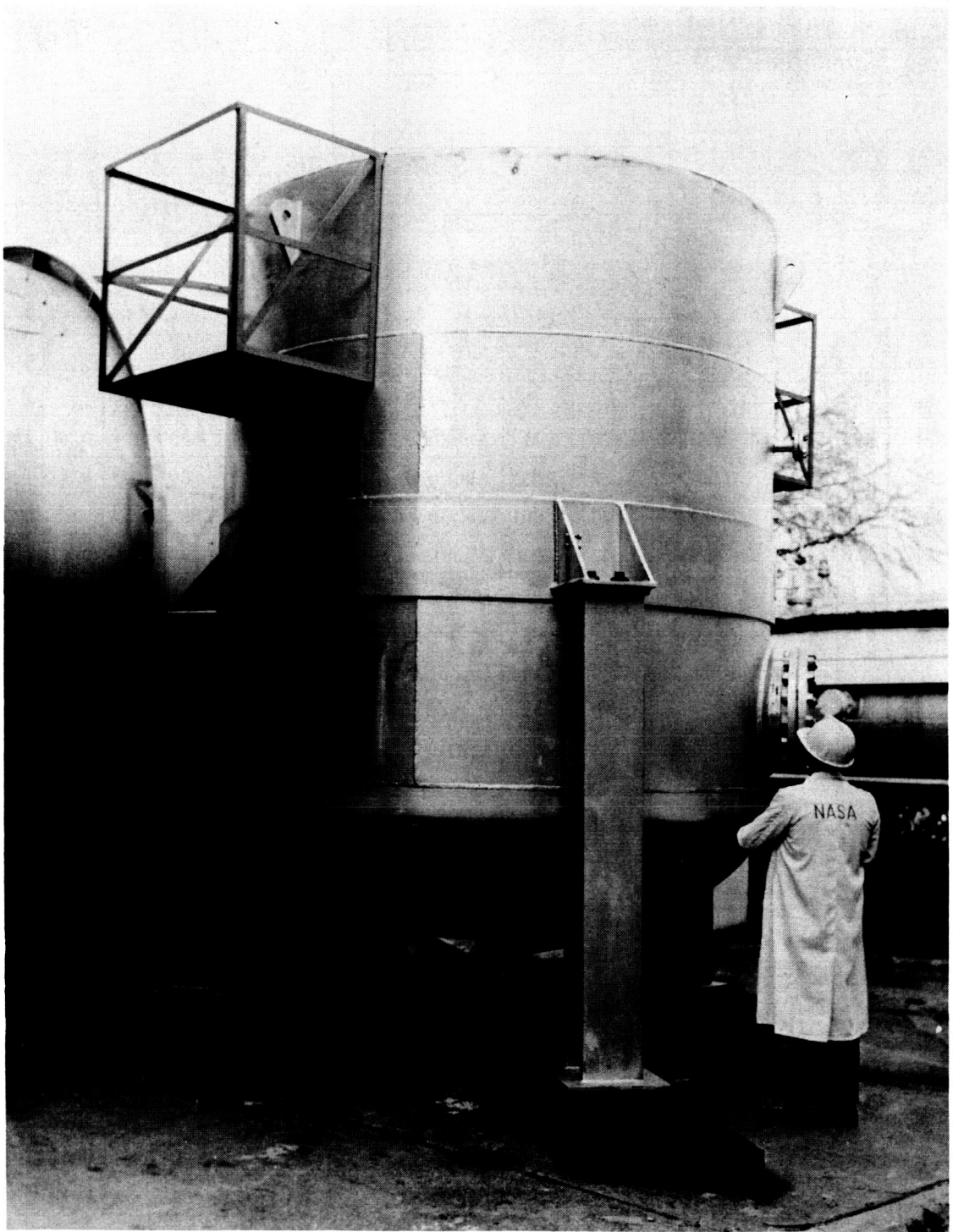
TABLE I.- DIMENSIONS AND PHYSICAL PROPERTIES OF BAFFLES



Tank diameter		D		D ₁		t		Material	E		ν	F
in.	cm	in.	cm	in.	cm	in.	cm		lb/in. ²	N/cm ²		
112	284	5.6	14.2	4.1	10.4	0.125	0.317	Aluminum	100×10^5	689×10^4	0.33	2.81×10^{-6}
112	284	5.6	14.2	4.1	10.4	0.032	0.081	Aluminum	100×10^5	689×10^4	0.33	1.63×10^{-4}
112	284	5.6	14.2	4.1	10.4	0.020	0.051	Aluminum	100×10^5	689×10^4	0.33	6.75×10^{-4}
112	284	5.6	14.2	4.1	10.4	0.008	0.020	Aluminum	100×10^5	689×10^4	0.33	8.80×10^{-3}
112	284	5.6	14.2	4.1	10.4	0.010	0.025	Mylar	6×10^5	41.4×10^4	0.40	8.50×10^{-2}
112	284	5.6	14.2	4.1	10.4	0.0075	0.019	Mylar	6×10^5	41.4×10^4	0.40	2.03×10^{-1}
30	76.2	1.5	3.81	1.0	2.54	0.0625	0.159	Stainless steel	300×10^5	2068×10^4	0.25	3.03×10^{-8}
30	76.2	1.5	3.81	1.0	2.54	0.010	0.025	Polyethylene	0.25×10^5	1.72×10^4	0.40	7.92×10^{-3}
30	76.2	1.5	3.81	1.0	2.54	0.003	0.008	Mylar	6×10^5	41.4×10^4	0.40	2.20×10^{-2}

TABLE II.- NATURAL FREQUENCIES OF SLOSH

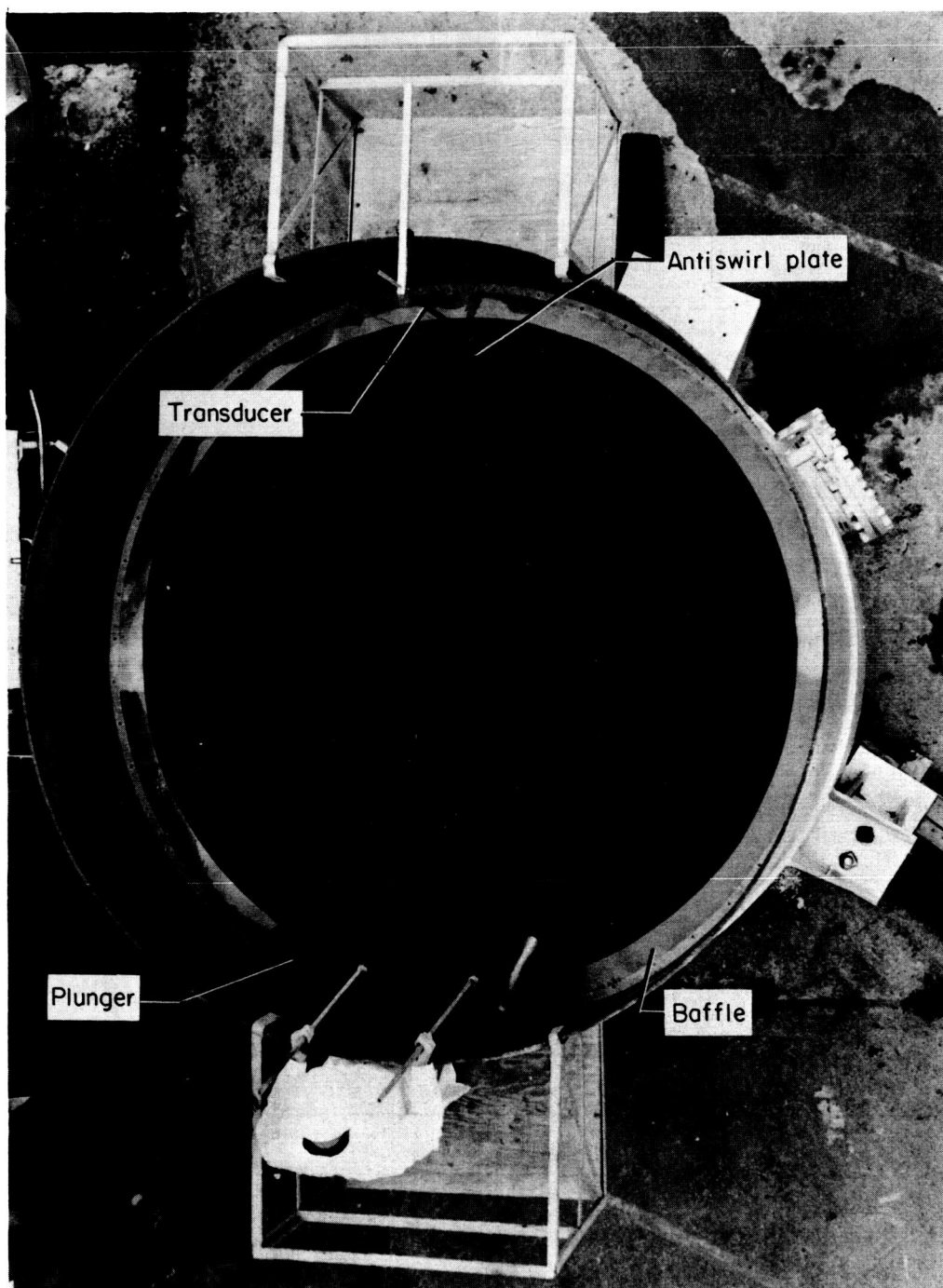
Tank diameter		F	Theoretical frequency	Experimental frequency			Frequency ratio, f_e/f_t		
in.	cm			d/R = 0.2	d/R = 0.3	d/R = 0.4	d/R = 0.2	d/R = 0.3	d/R = 0.4
112	284	2.81×10^{-6}	0.5669	0.5522	0.5565	0.5587	0.9741	0.9817	0.9855
112	284	1.63×10^{-4}	0.5669	0.5510	0.5550	0.5575	0.9719	0.9790	0.9834
112	284	6.75×10^{-4}	0.5669	0.5512	0.5558	0.5590	0.9723	0.9804	0.9861
112	284	8.80×10^{-3}	0.5669	0.5523	0.5570	0.5600	0.9743	0.9825	0.9878
112	284	8.50×10^{-2}	0.5669	0.5558	0.5590	0.5615	0.9804	0.9861	0.9905
112	284	2.03×10^{-1}	0.5669	0.5577	0.5598	0.5615	0.9838	0.9875	0.9905
30	76.2	3.03×10^{-8}	1.095	1.0654	1.0752	-----	0.9729	0.9819	-----
30	76.2	7.92×10^{-3}	1.095	1.0694	1.0784	-----	0.9766	0.9848	-----
30	76.2	2.20×10^{-2}	1.095	1.0686	1.0788	-----	0.9758	0.9852	-----



(a) General view.

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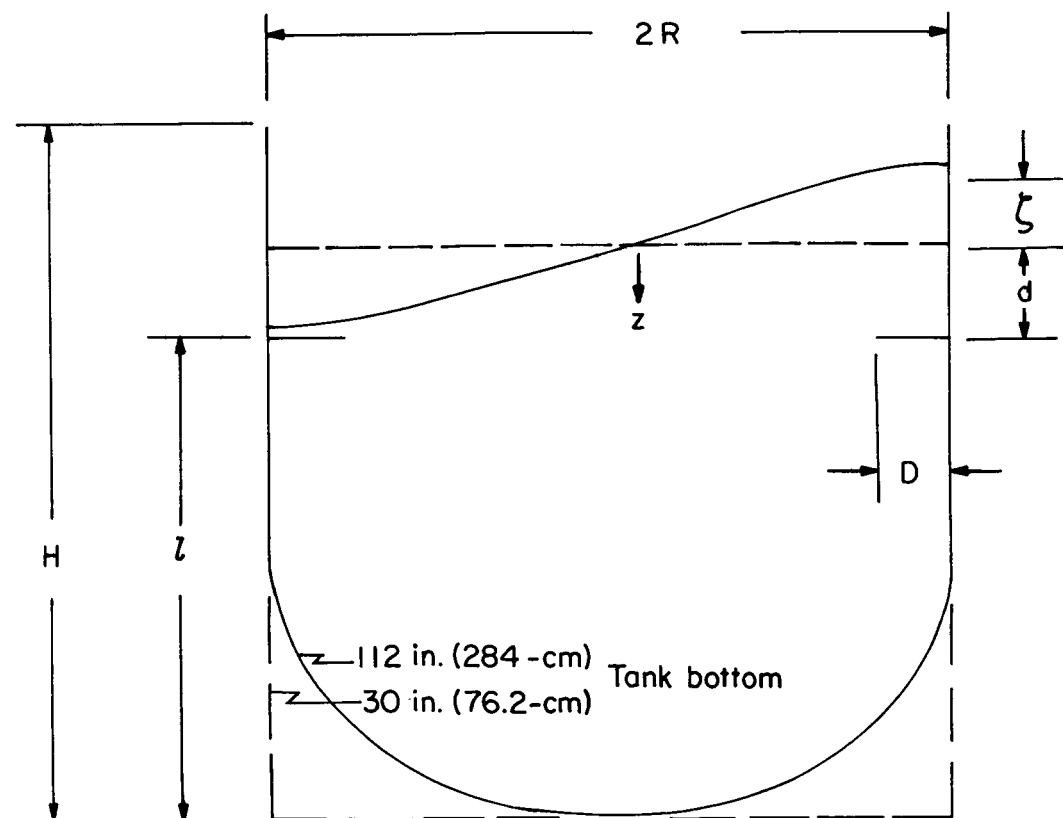
Figure 1.- 112-inch (284-cm) diameter slosh tank.



(b) Plan view.

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Figure 1.- Concluded.



Tank diameter		R		D		H		l		d/R
in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	
112	284	56	142	5.6	14.2	148	376	112	284	0.2 to 0.4
30	76.2	15	38.1	1.5	3.81	30.6	77.7	22	55.8	0.2 to 0.3

Figure 2.- Dimensions of slosh tanks.

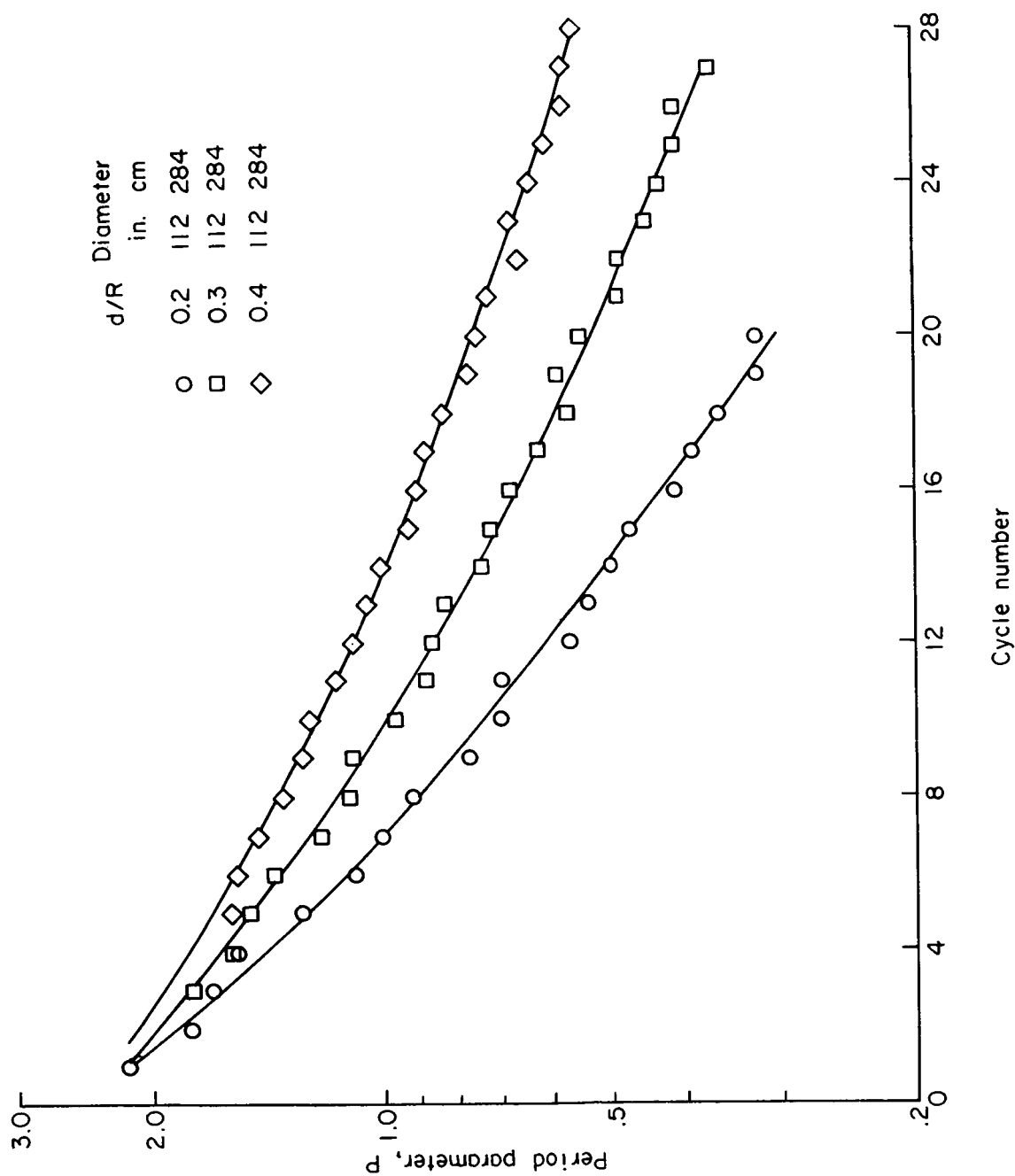


Figure 3.- Sample damping data. Medium flexibility baffle ($F = 8.8 \times 10^{-3}$).

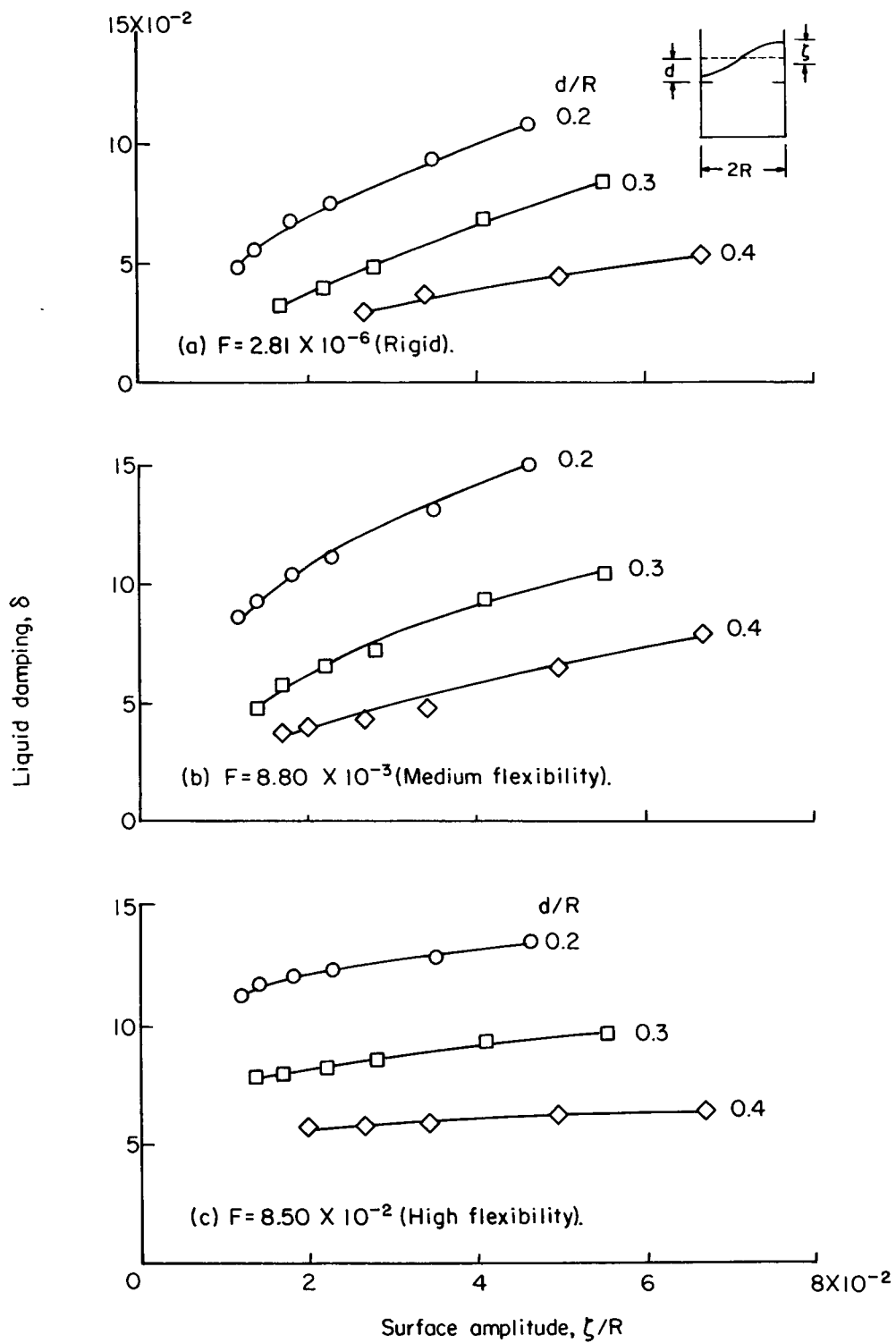


Figure 4.- Effect of surface amplitude on liquid damping for various locations of rigid and flexible baffles. 112-inch (284-cm) diameter tank.

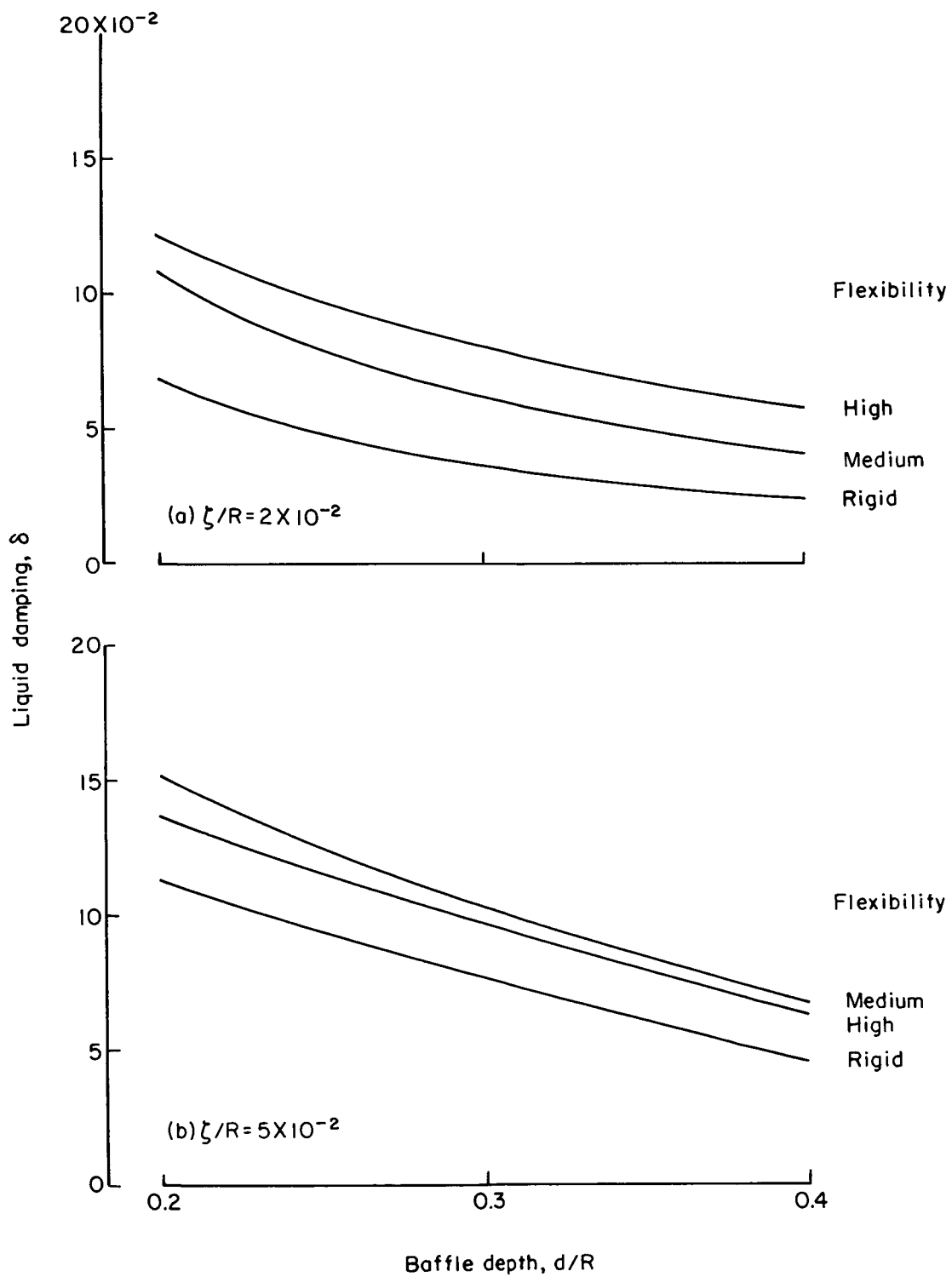


Figure 5.- Effect of baffle depth on liquid damping for rigid and flexible baffles. 112-inch (284-cm) diameter tank.

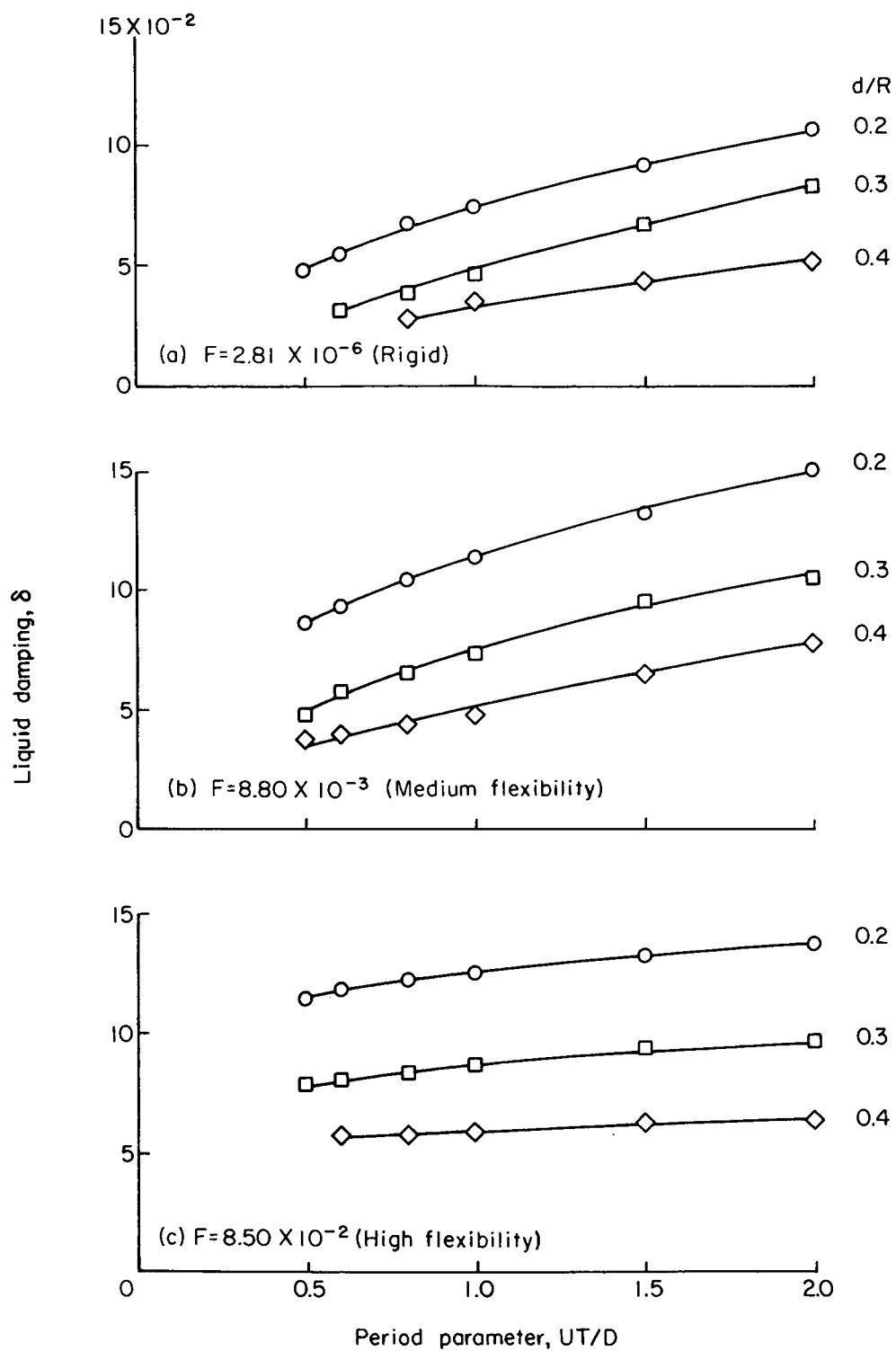


Figure 6.- Effect of period parameter on liquid damping for various locations of rigid and flexible baffles. 112-inch (284-cm) diameter tank.

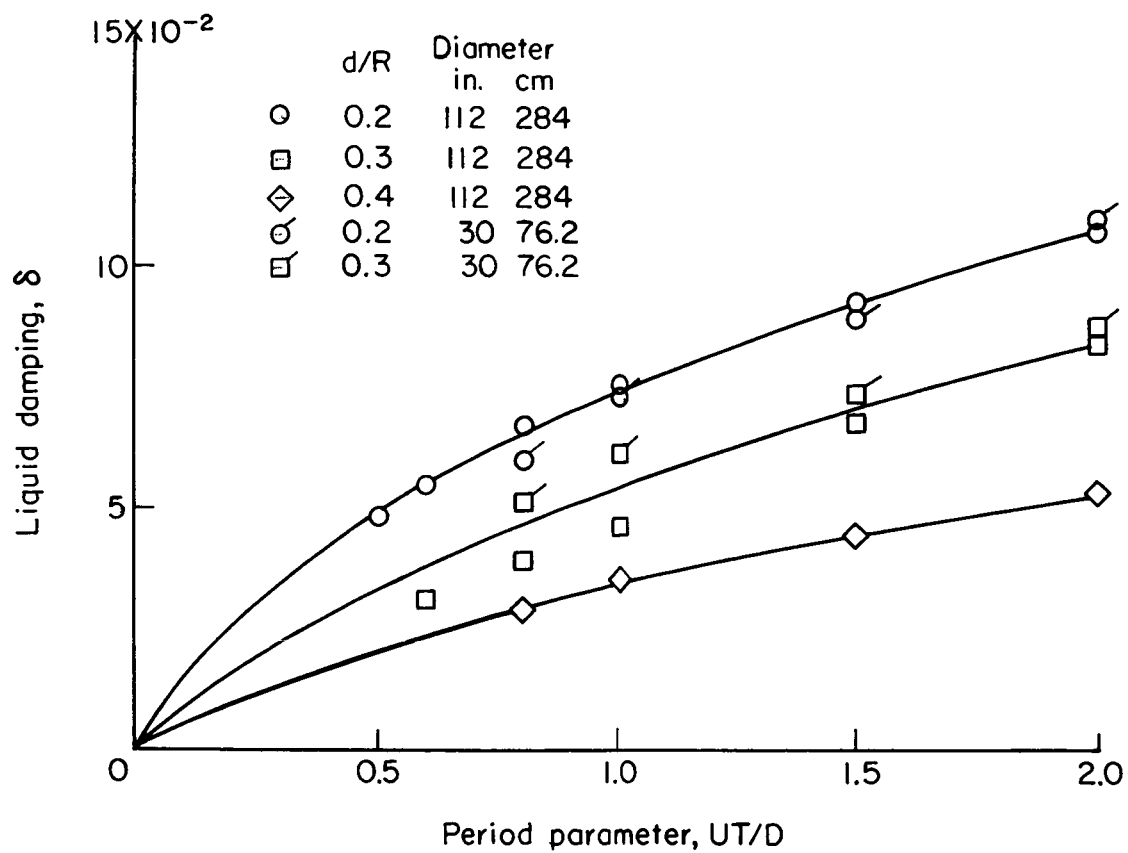


Figure 7.- Effect of tank diameter on liquid damping for various locations of rigid baffles.

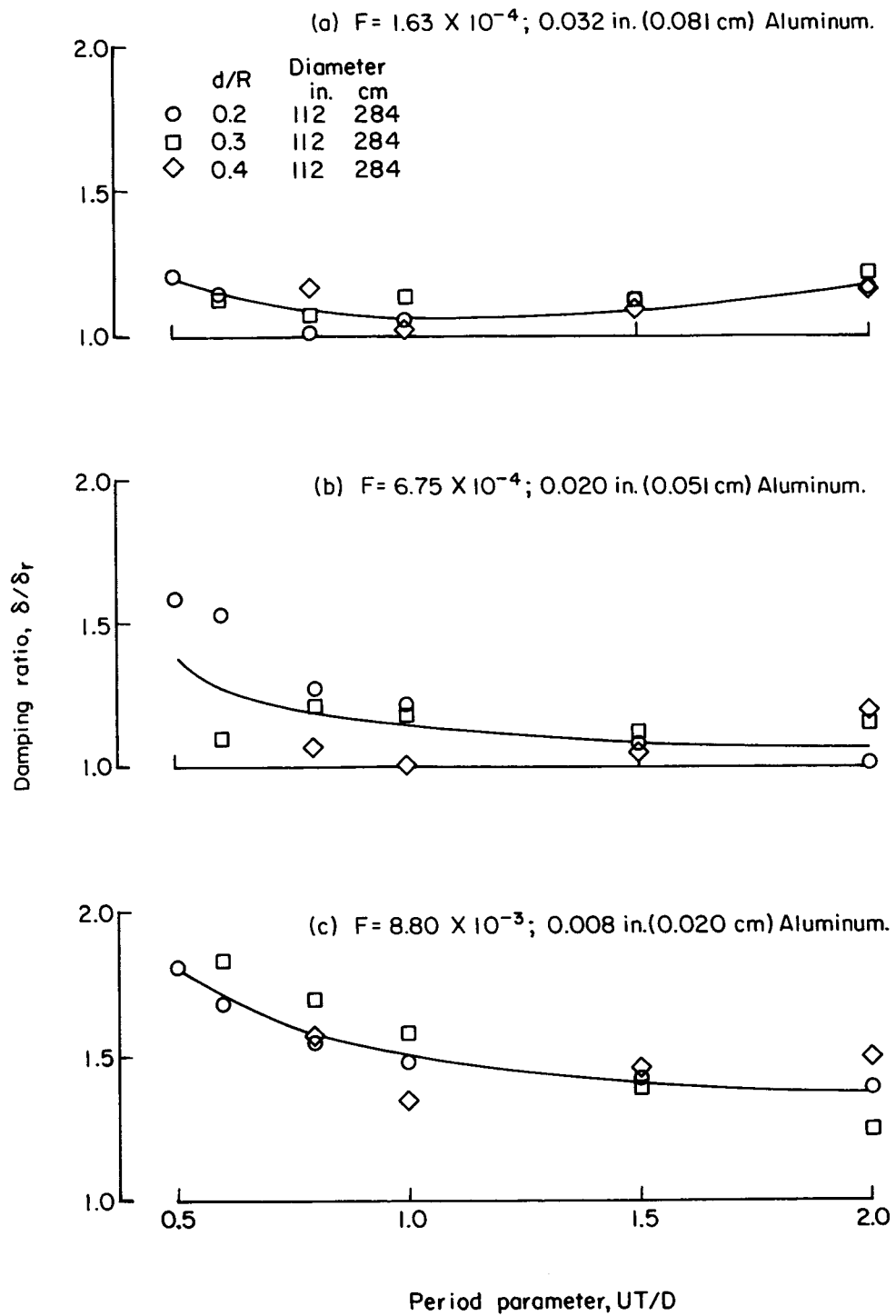


Figure 8.- Dependency of relative damping on period parameter for each baffle flexibility.

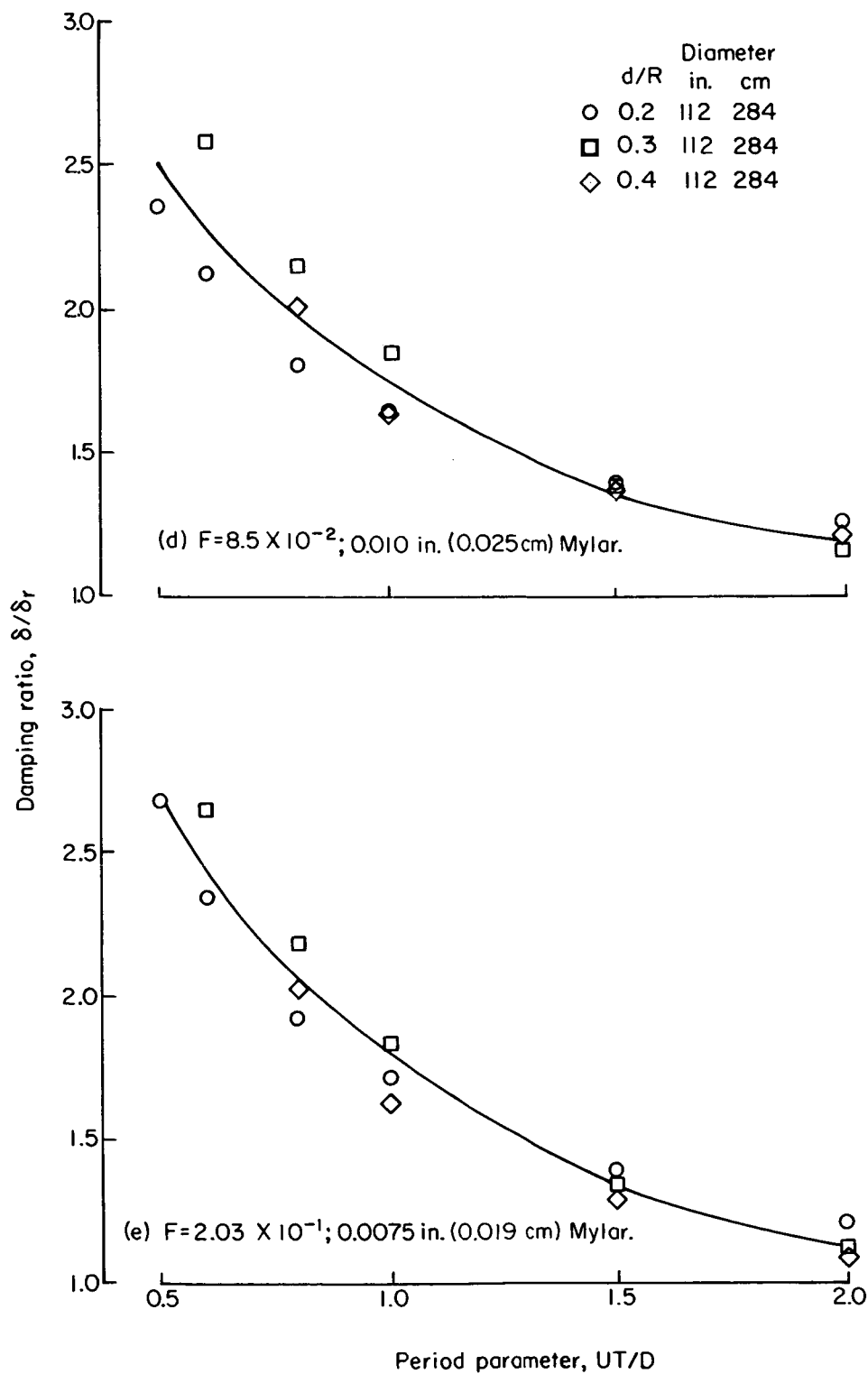


Figure 8.- Continued.

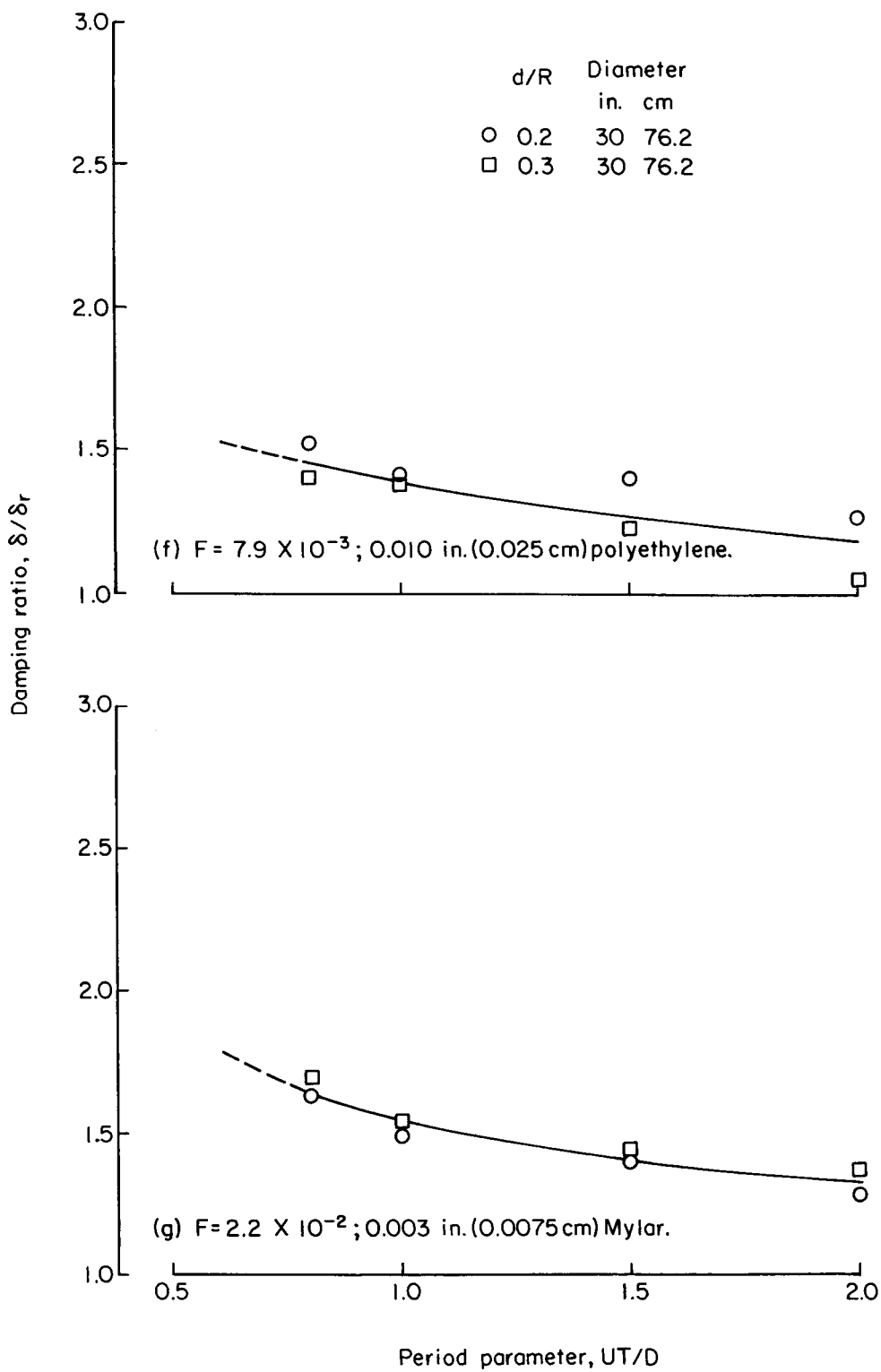


Figure 8.- Concluded.

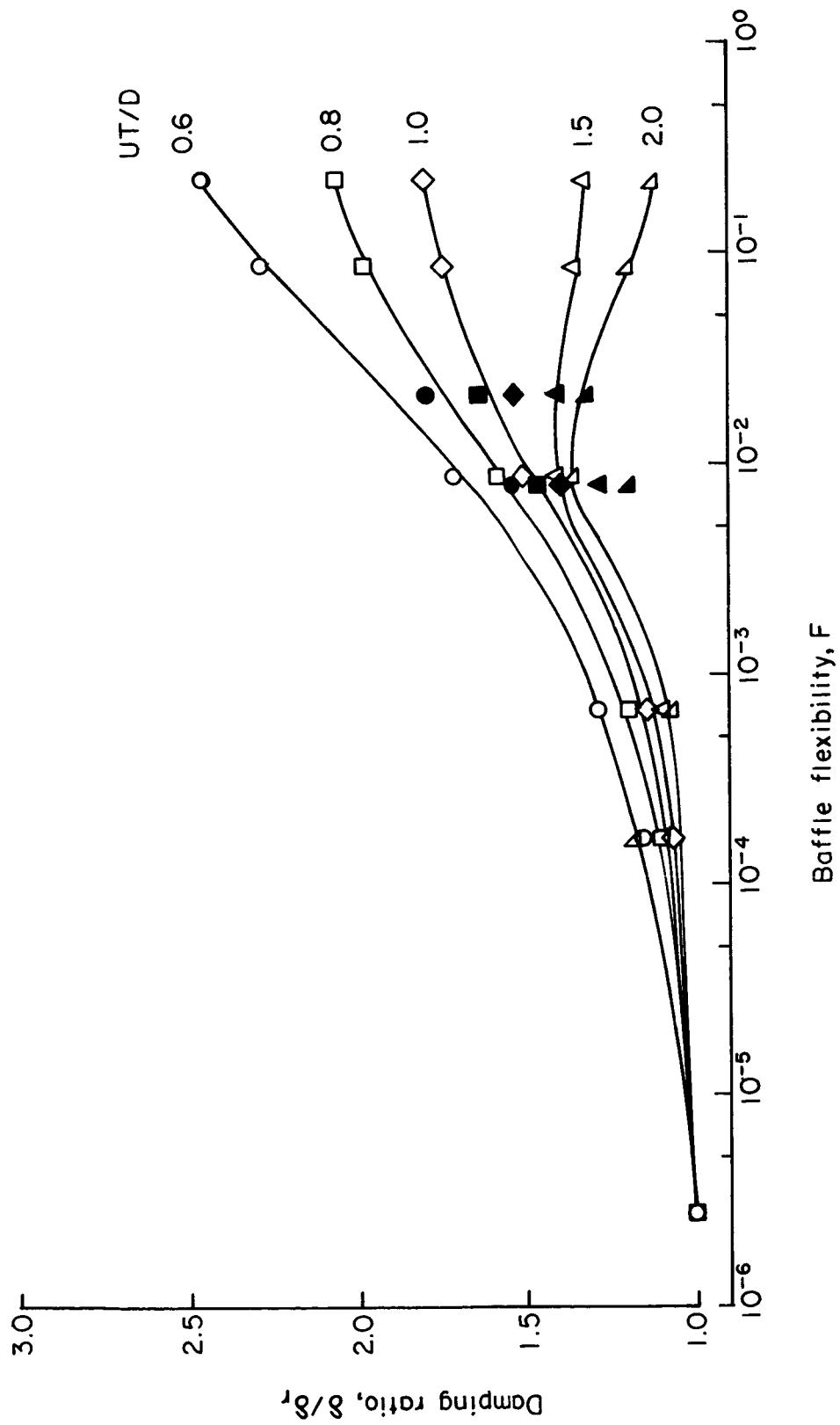


Figure 9.- Dependency of relative damping on baffle flexibility for a range of period parameters. Solid symbols represent 30-inch-diameter tank data.

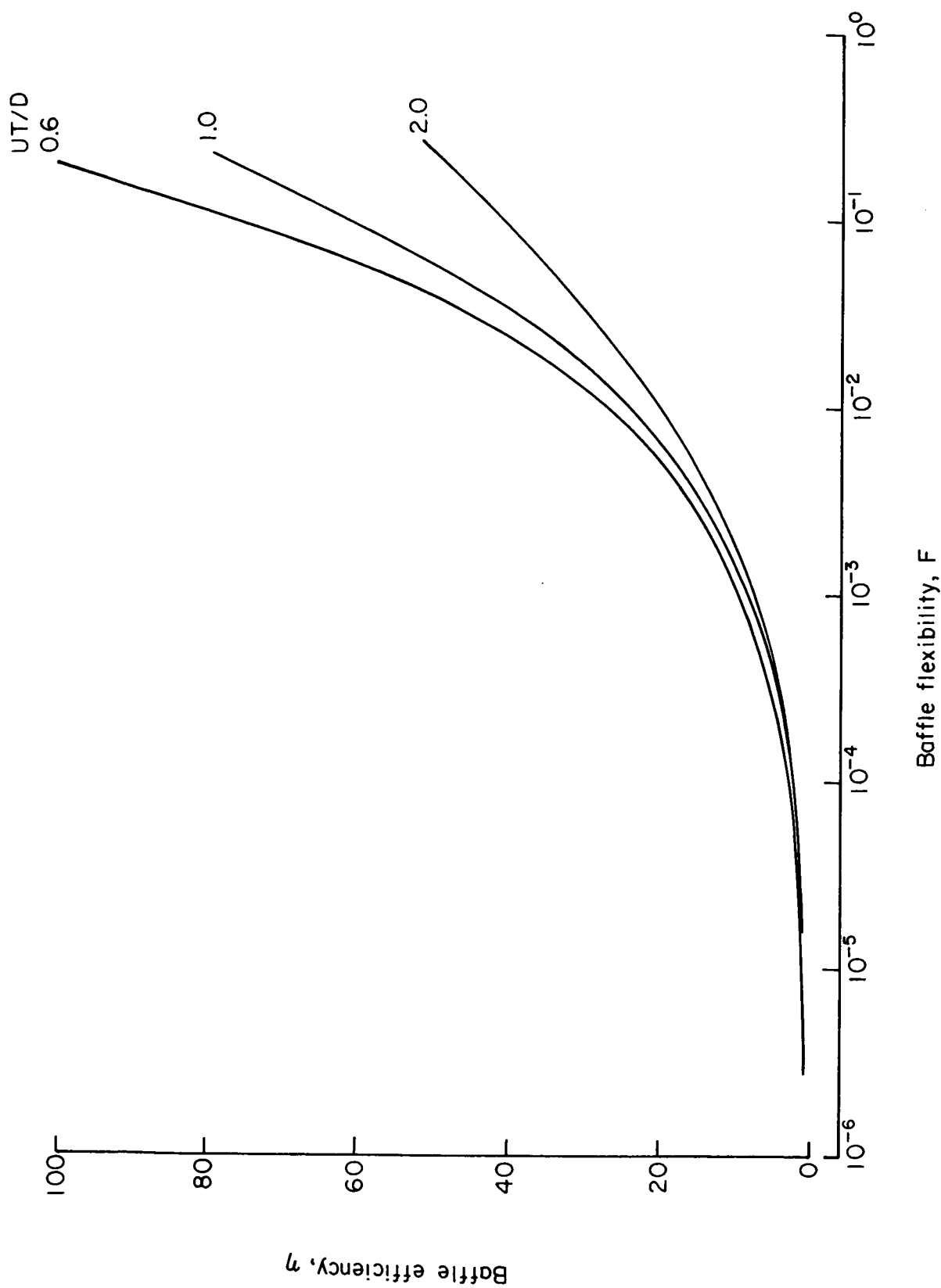


Figure 10.- Variation of baffle efficiency with baffle flexibility. $t_r = 0.125$ inch.

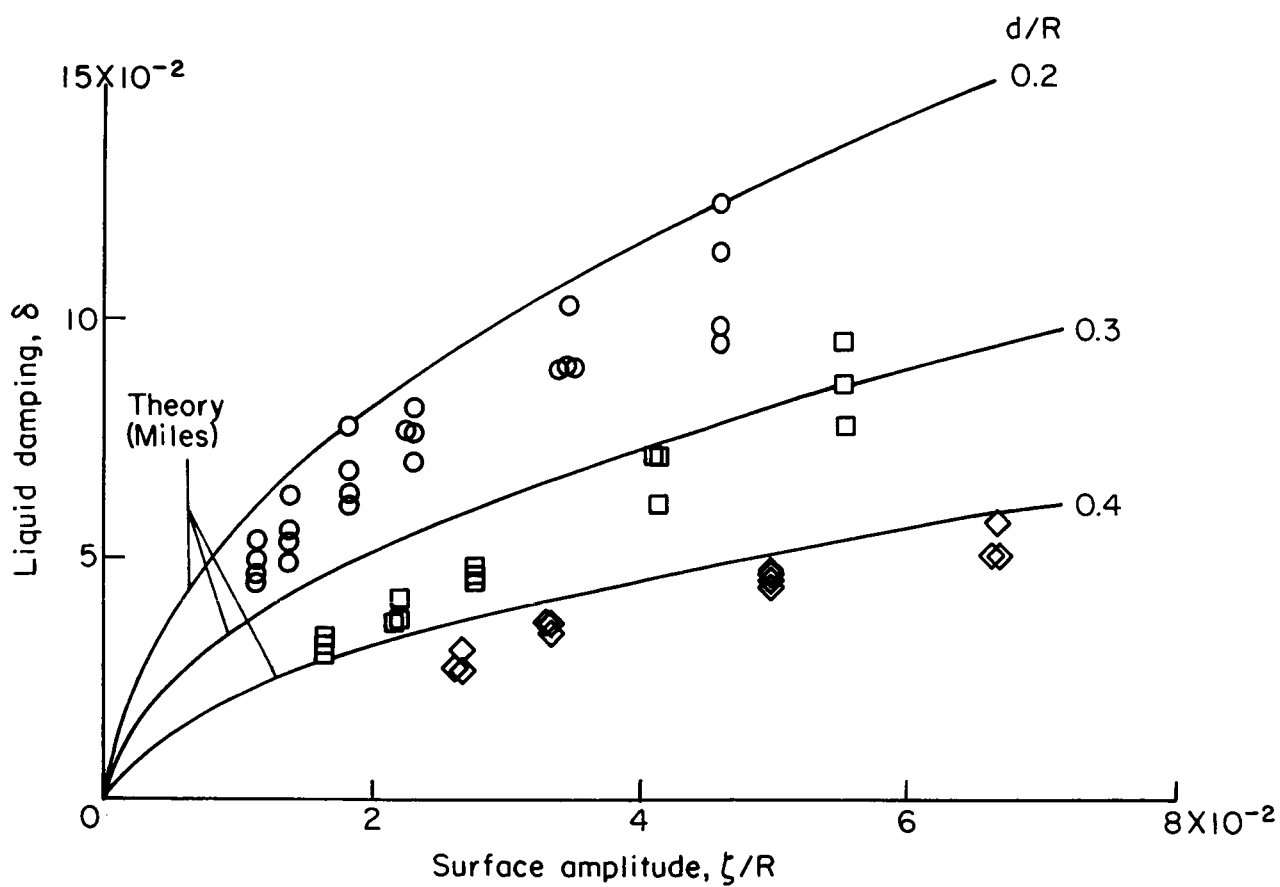


Figure 11.- Rigid baffle data distribution and comparison with theory. 112-inch (284-cm) diameter tank.

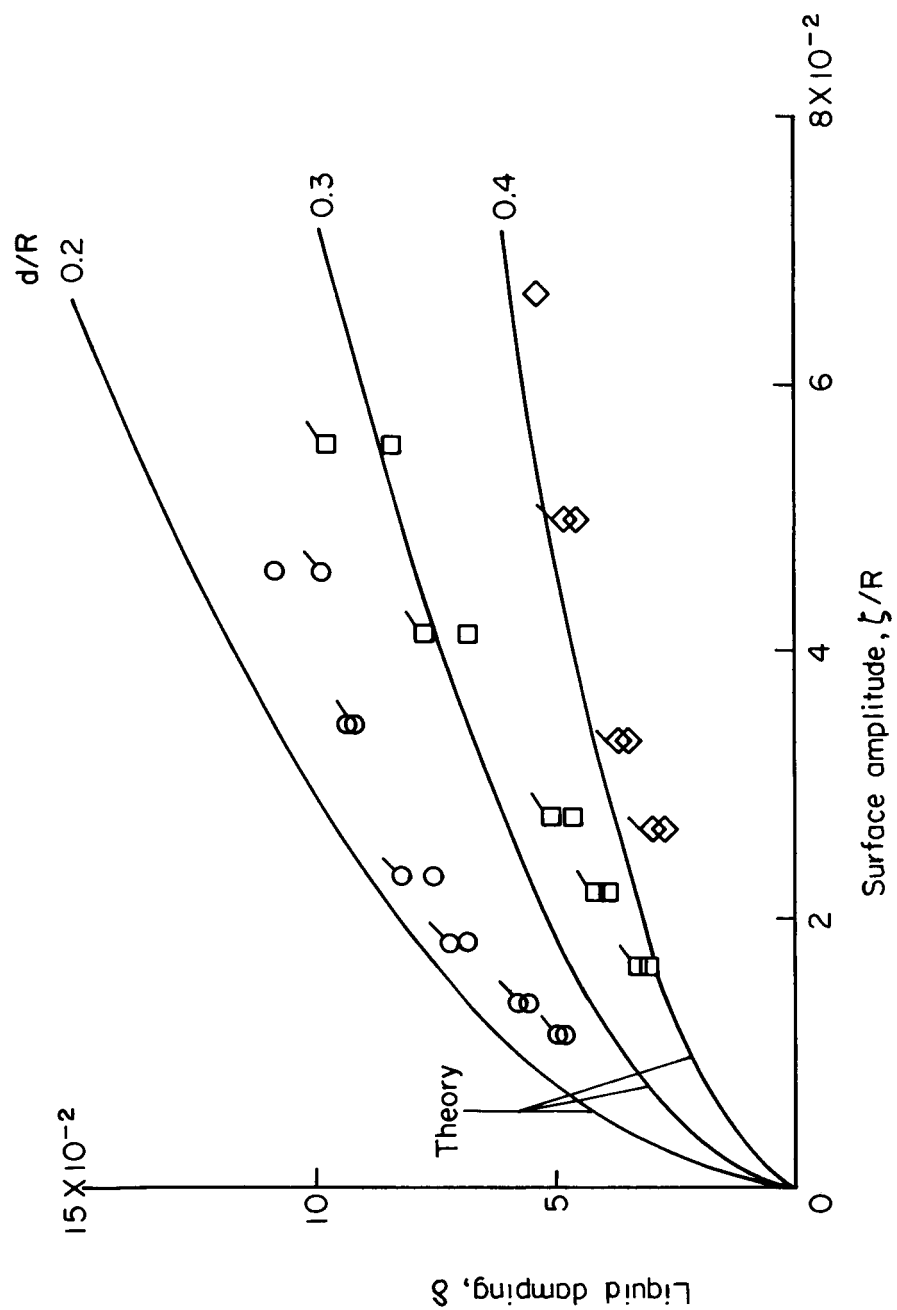


Figure 12.- Effect of baffle edge condition on liquid damping. 112-inch (284-cm) diameter tank. Flagged symbols are for sharp edge baffle.

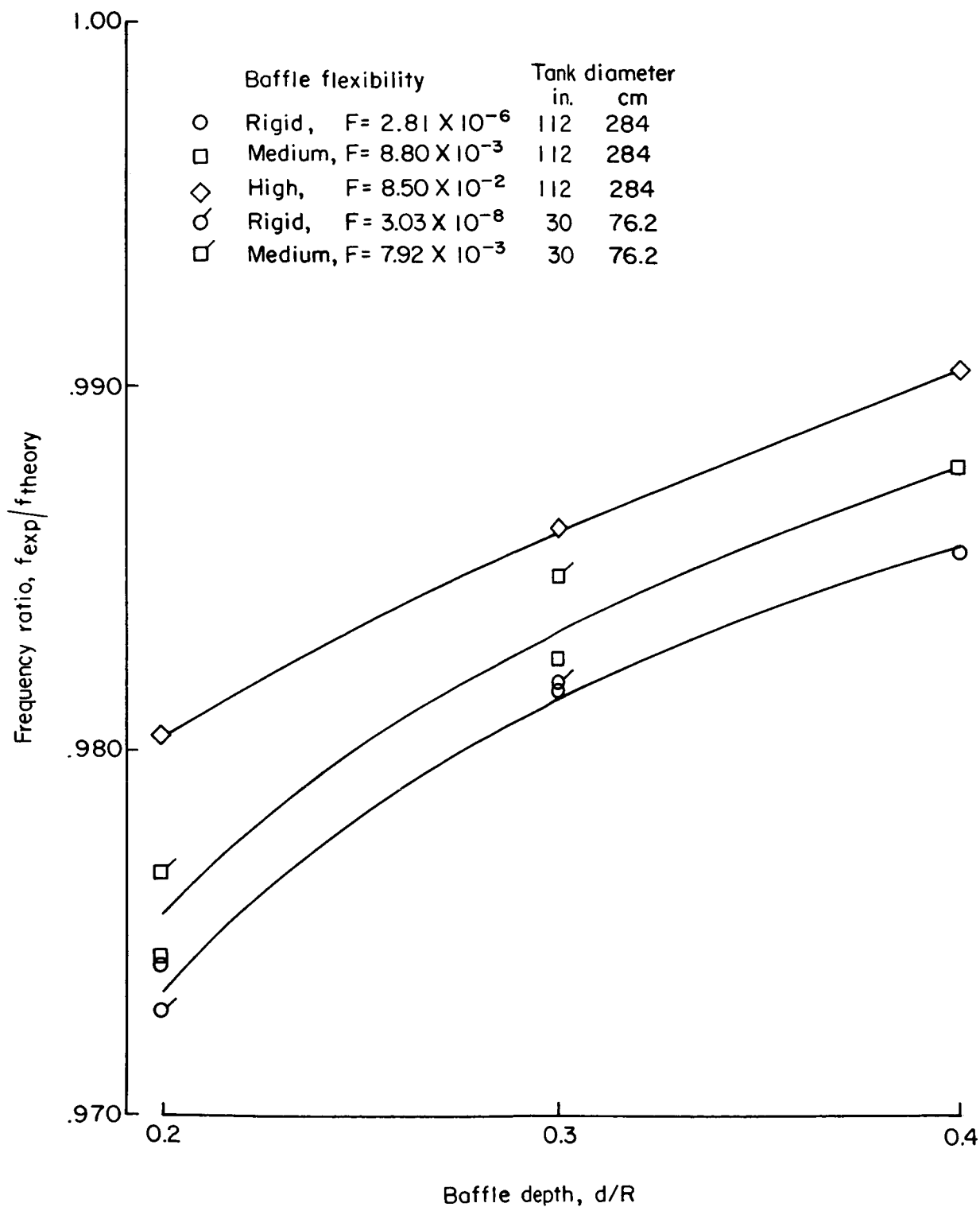


Figure 13.- Variation of natural frequency with baffle location for rigid and flexible baffles.